A satellite image of the California Current System, showing the coastline of California and the surrounding ocean. The ocean is dark blue, and the land is a mix of brown and green. The image is taken from a high angle, showing the curvature of the Earth.

Pattern and dynamics of SST fronts in the California Current System

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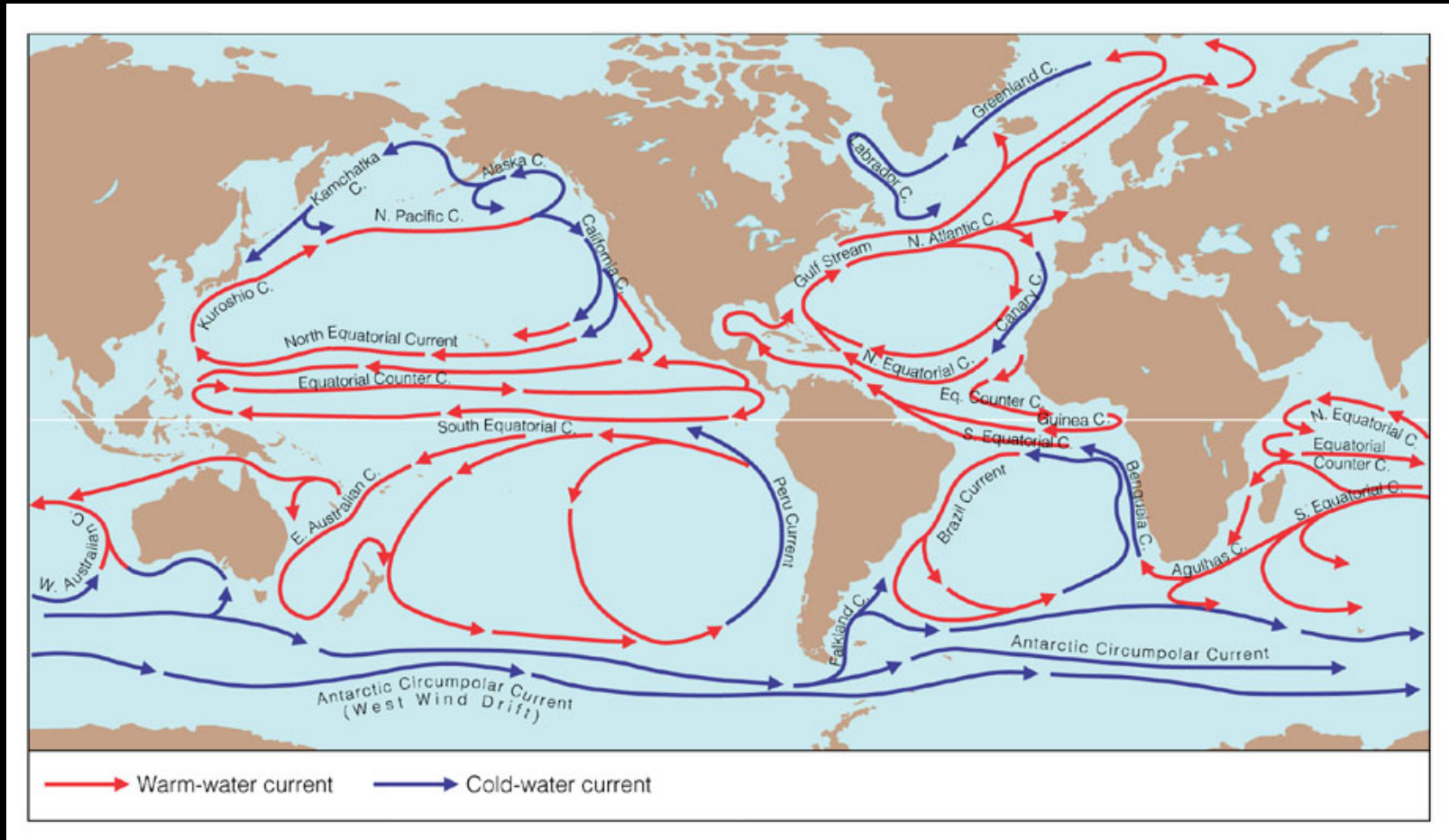


CASPO Seminar Series
Scripps Institution of Oceanography
UC San Diego

Outline

- Context
- Motivation
- Fronts dynamics
- Simulation results
- Summary

Eastern Boundary Current Systems



Coastal upwelling

There are four major coastal upwelling regions:

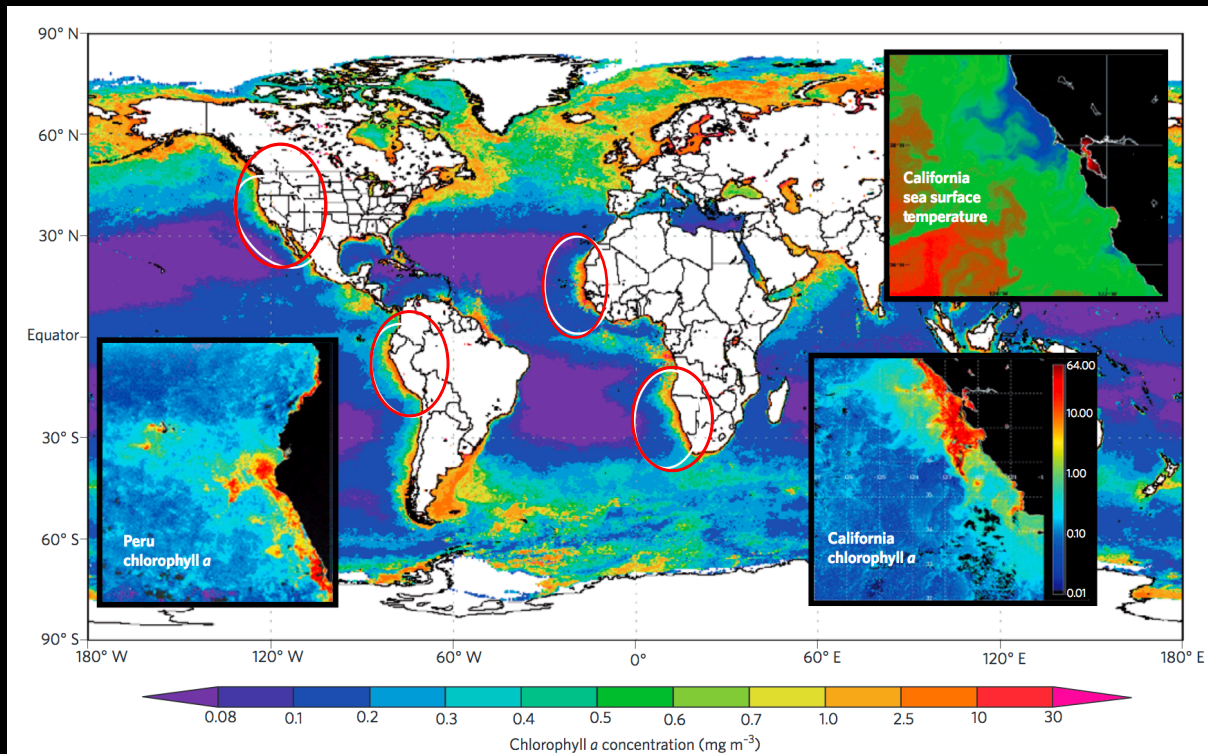
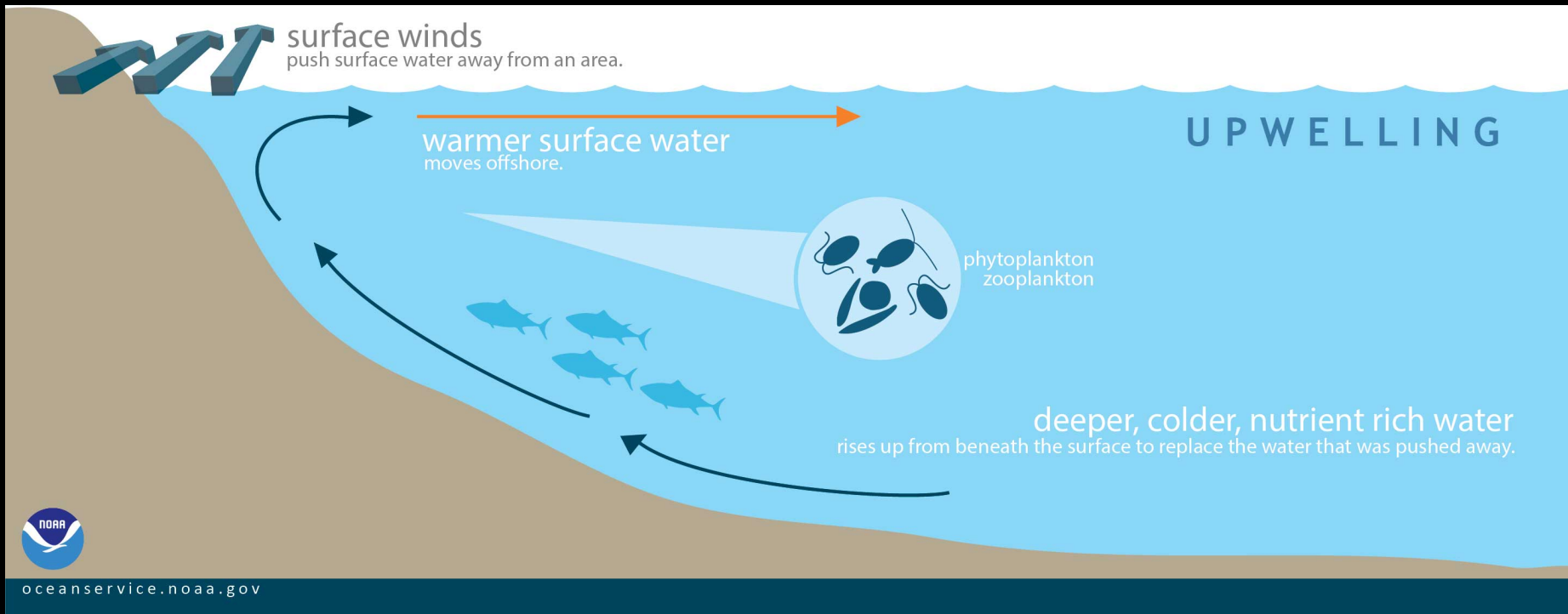


Figure 1 | Locations of the four main coastal upwelling systems associated with eastern boundary currents. A global false-colour compilation of satellite data on ocean chlorophyll *a* from the MODIS Aqua sensor for the year 2011 shows the California, Peru, Canary and Benguela ecosystems (white ovals). Also shown are close-up views of chlorophyll *a* levels in upwelling-supported phytoplankton blooms in Peru (lower left inset) and California (lower right inset), as well as a satellite-derived view of sea surface temperature in cold, nutrient-rich upwelling plumes off California (upper right inset). Satellite imagery courtesy of NASA.

From Capone
and Hutchins,
2013.

Coastal upwelling

Coastal upwelling occurs when wind blows along the coast, causing surface waters to be displaced offshore and replaced by deeper waters:



Coastal upwelling

Coastal upwelling regions are « hot spots » of biological activity and are typically considered as large marine ecosystems.

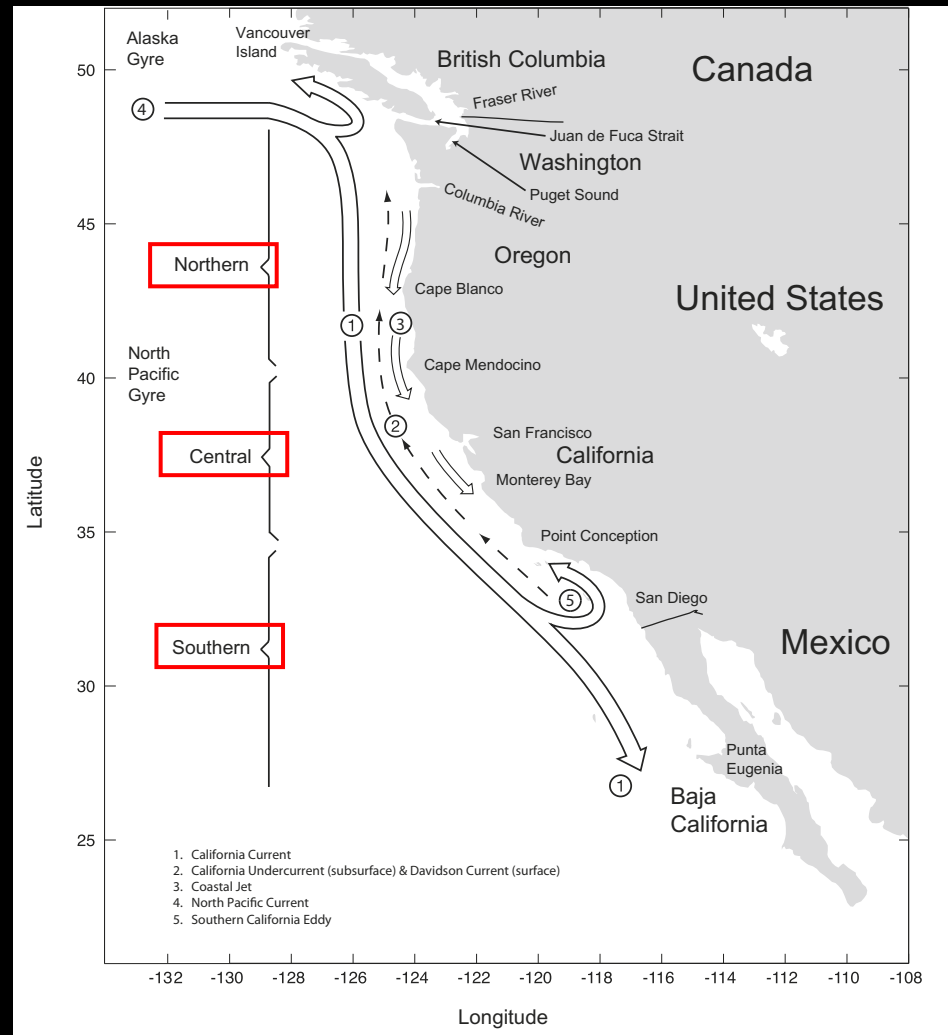
These regions represent $\sim 1\%$ of the global ocean's area, but amount to over 20% of the global fisheries catch.

They are associated with the Eastern Boundary Current Systems, and we will focus on the California Current System in this study.

Geography of the CCS

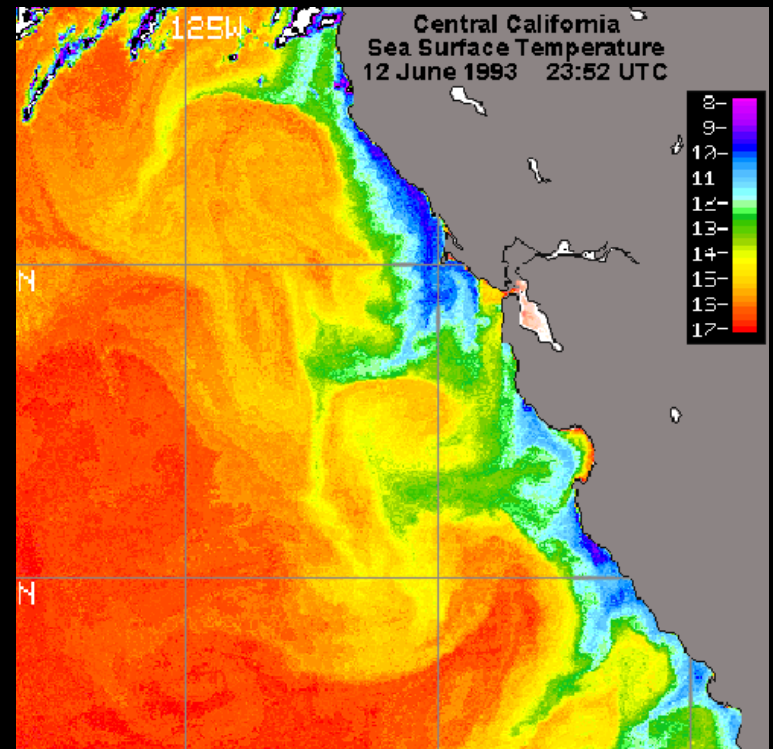
The California Current System (CCS) encompasses the California State and extends from 50°N to 20°N, and offshore to 135°W. It is often divided into three regions: northern, central and southern CCS.

From Checkley and Barth, 2009.



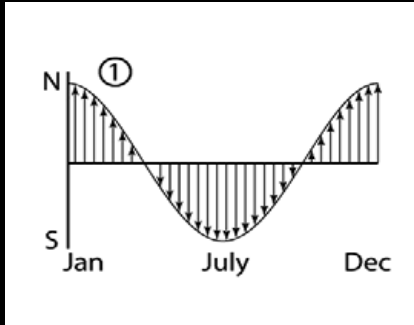
SST fronts

- **Fronts** are narrow boundaries between water masses of different properties.
- **Sea surface temperature (SST) fronts** separate water masses with different SST.
- **SST upwelling fronts** are due to the contrasting temperatures of the upwelled (cold) waters and of the surface (warm) waters.



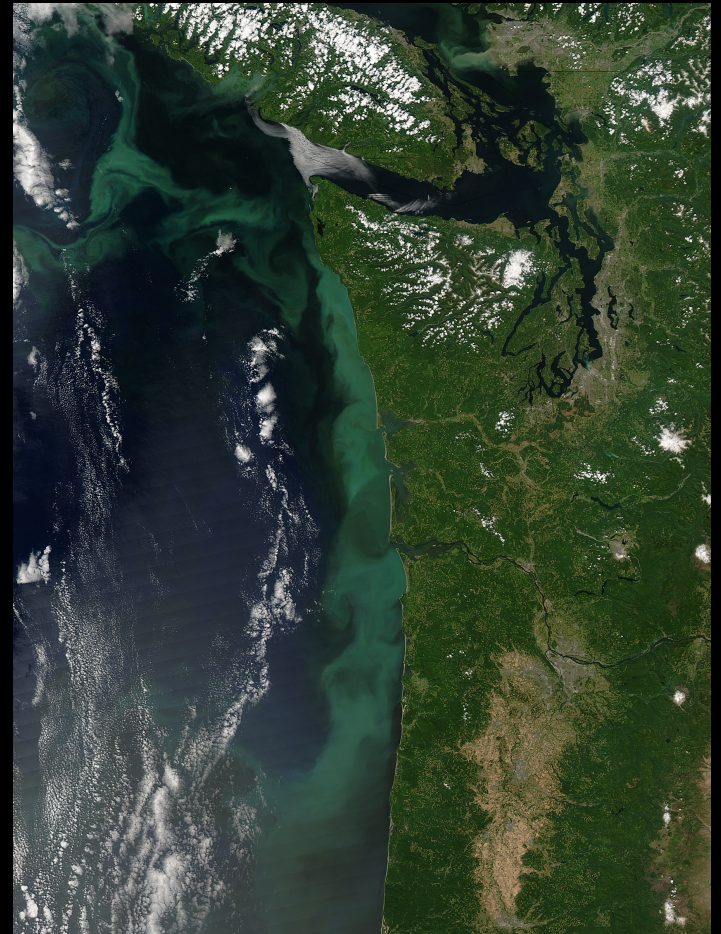
Courtesy of E. Armstrong, JPL

Northern CCS



In the northern CCS, winds have a seasonal pattern and are equatorward from

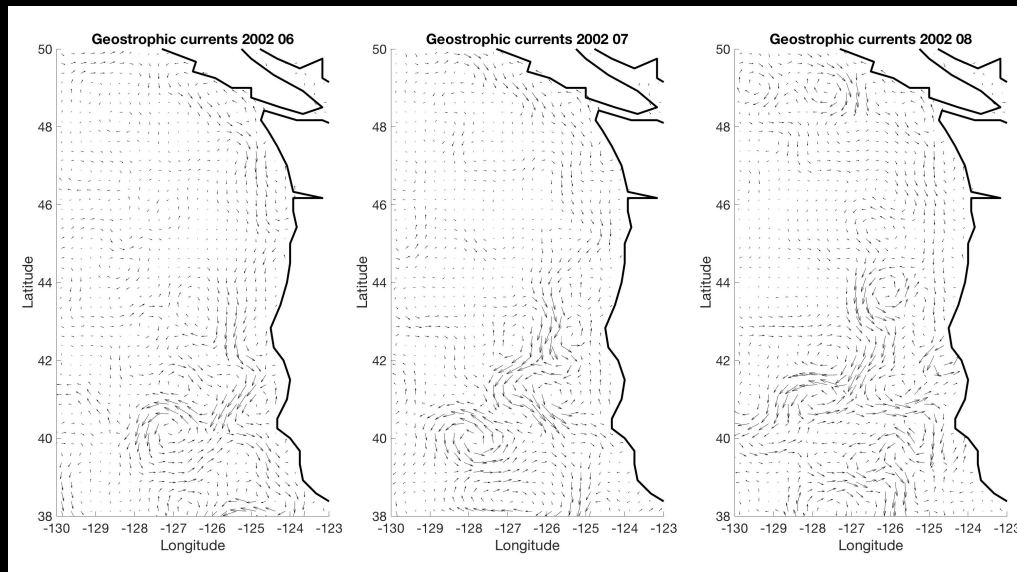
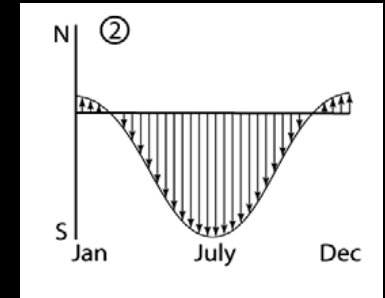
Spring to Fall (i.e. coastal upwelling favorable). Over that period, a narrow and fast coastal upwelling jet develops. Fronts are typically found at the edge of the jet.



NASA Earth Observatory

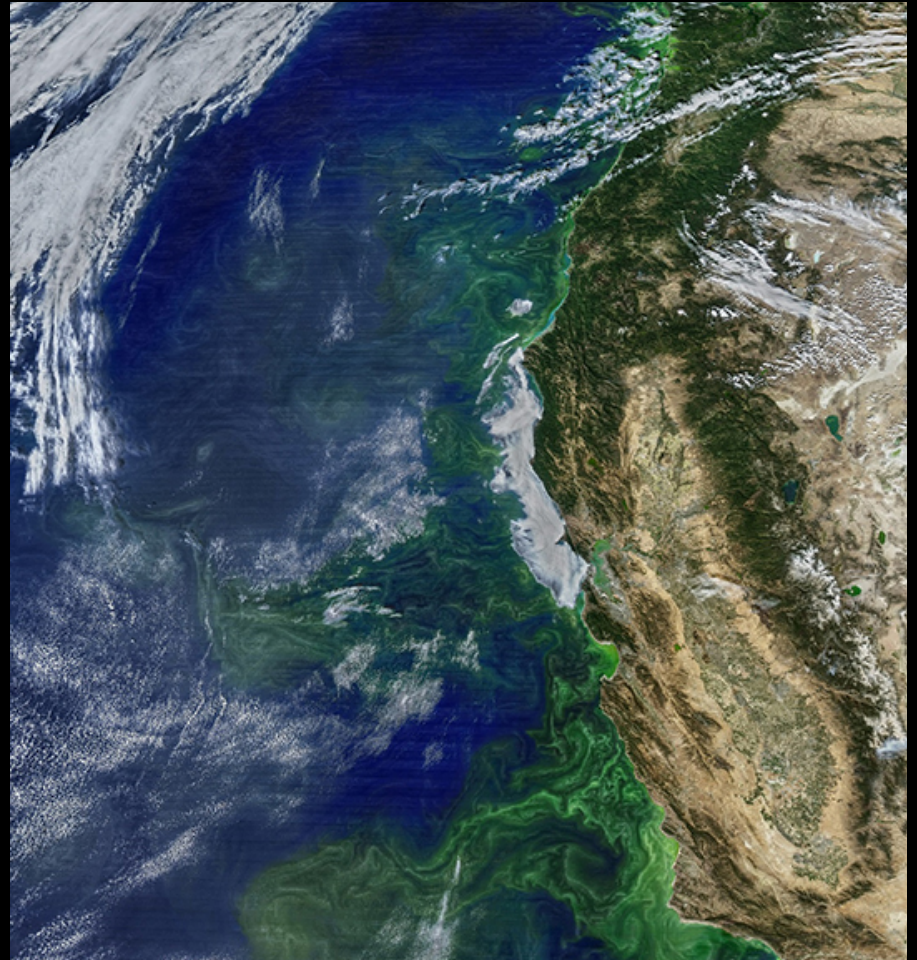
Central CCS

The peak of the season is in July. The coastal jet flows from the northern CCS and meanders: mesoscale eddies are formed past the Capes, and propagate offshore.



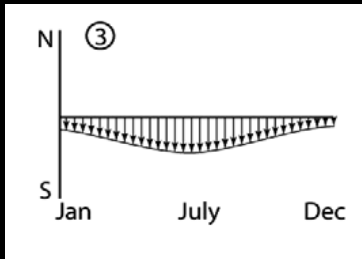
Central CCS

During the upwelling season, cold nutrient-rich waters are brought up to the surface, resulting in plankton blooms visible from space. The mesoscale eddies stir the upwelled waters to form long cold filaments (upwelling fronts).



NASA

Southern CCS



Despite upwelling-favorable winds year-round, the winds' intensity is much lower in the region, and coastal upwelling is observed in very localized areas.

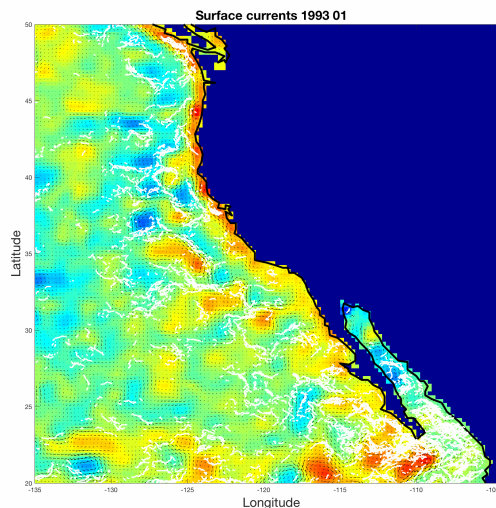


NASA

Satellite observations

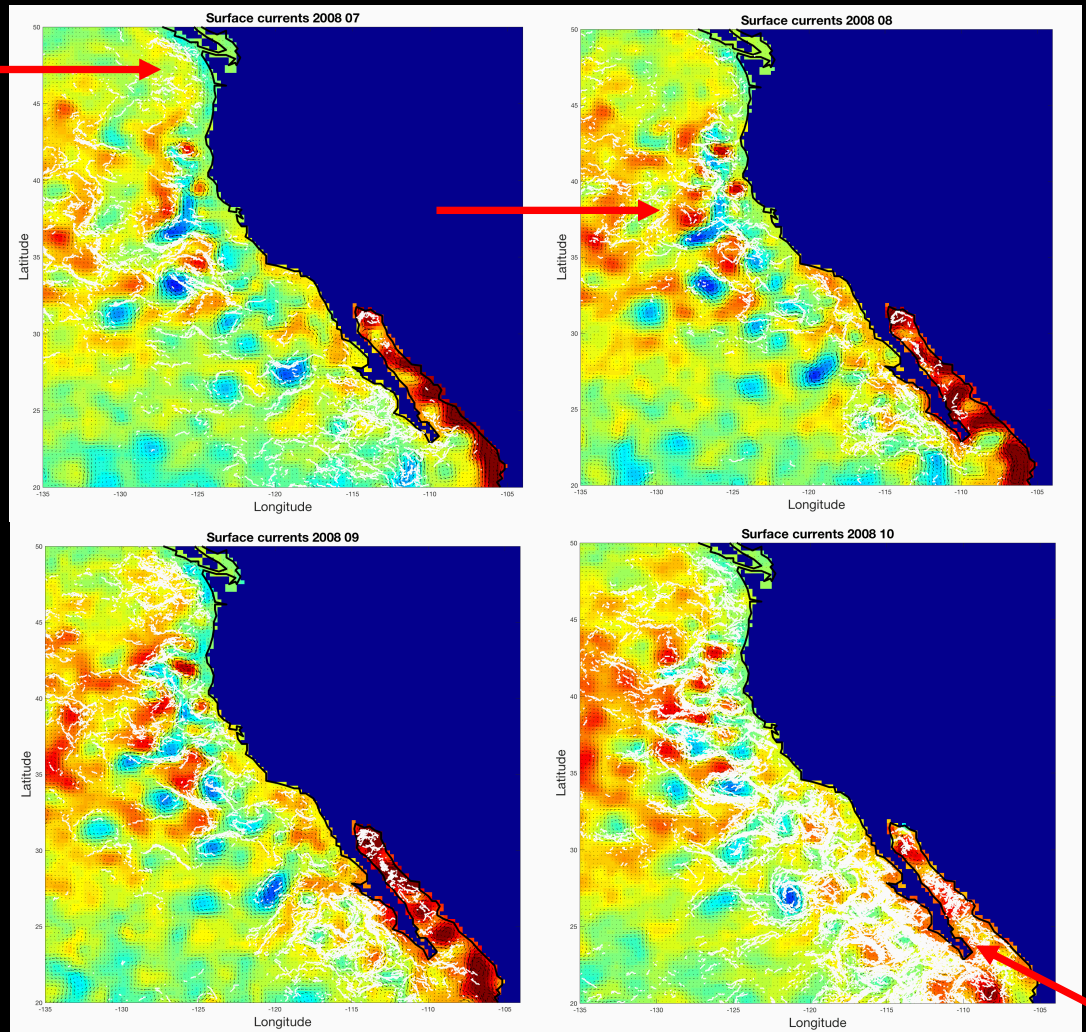
Altimetry and SST data were combined into monthly composite maps from 1993 to 2011:

- Monthly mean Sea Level Anomalies (SLA), from CMEMS
- Monthly aggregate of the SST fronts location, as detected by the Cayula-Cornillon algorithm applied to Pathfinder AVHRR



Satellite observations

SST fronts are typically found at the periphery of the mesoscale eddies. However, SST fronts were sometimes observed crossing geostrophic contours, especially in late Summer/Fall.



Motivation

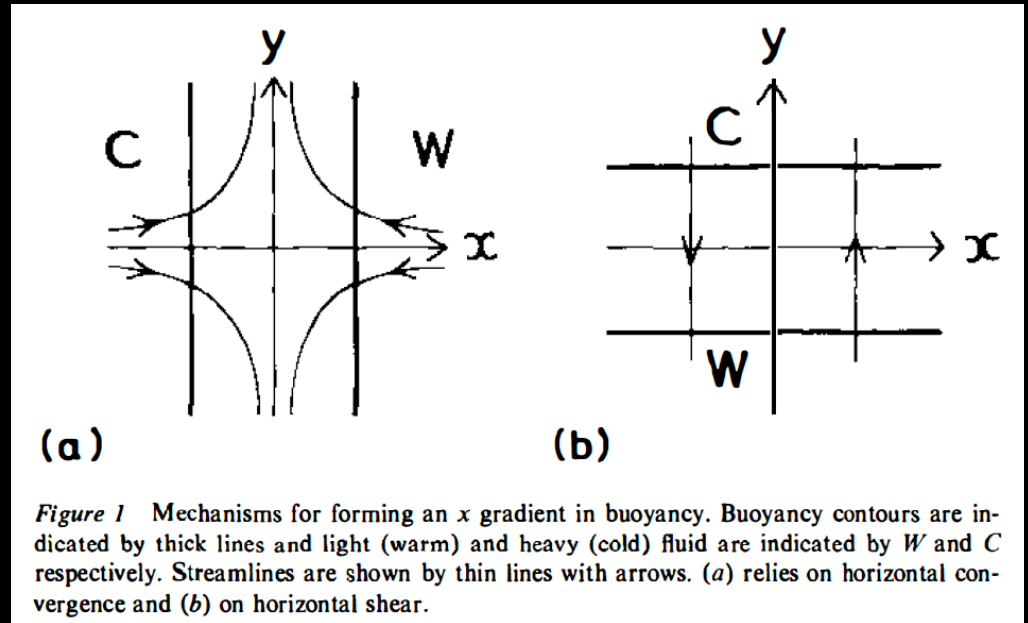
In the CCS, coastal upwelling occurs from **Spring to Fall**, mostly in the **northern** and **central CCS**. However, SST fronts are observed throughout the CCS, in particular after the coastal upwelling season, in the southern CCS.

This study=

Investigating the nature of the SST fronts found in the CCS **outside** of the coastal upwelling context.

Frontogenesis theory

The classical theory introduces horizontal convergence and horizontal shear as mechanisms for producing strain. The strain sharpens anomalies into strong gradients (fronts).

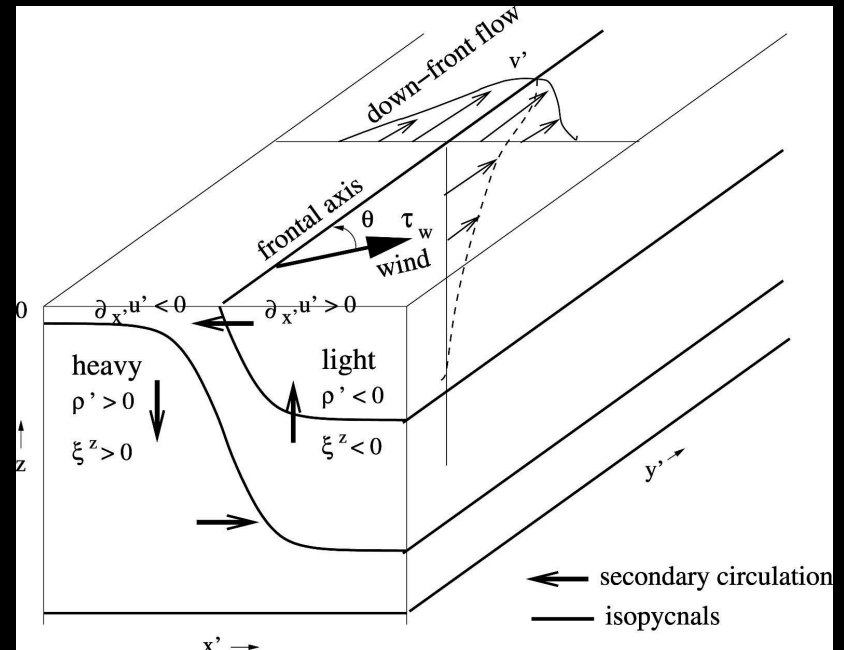
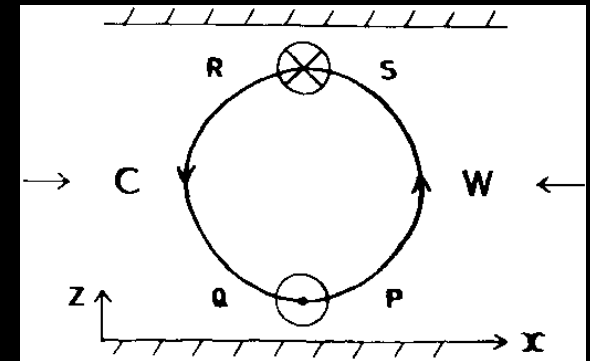


From Hoskins, 1982.

Frontogenesis theory

As the lateral gradients sharpen, the thermal wind balance is lost. A secondary, ageostrophic circulation occurs in the cross-frontal (vertical) direction in order to restore the balance. The stronger the gradient, the larger the vertical velocities.

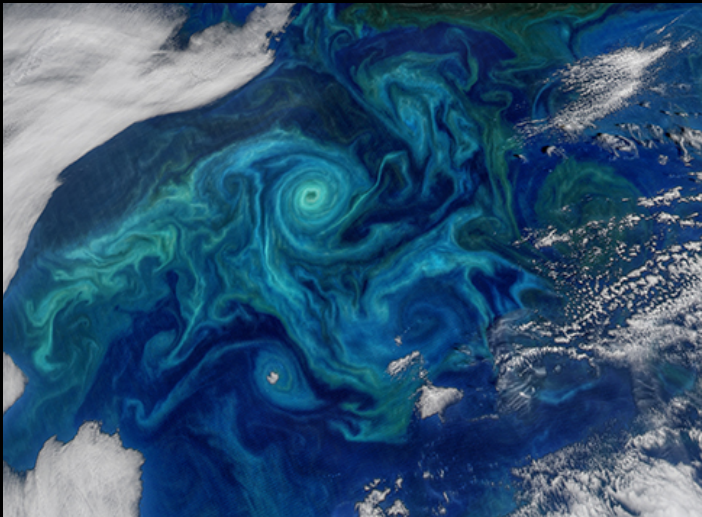
From Hoskins, 1982.



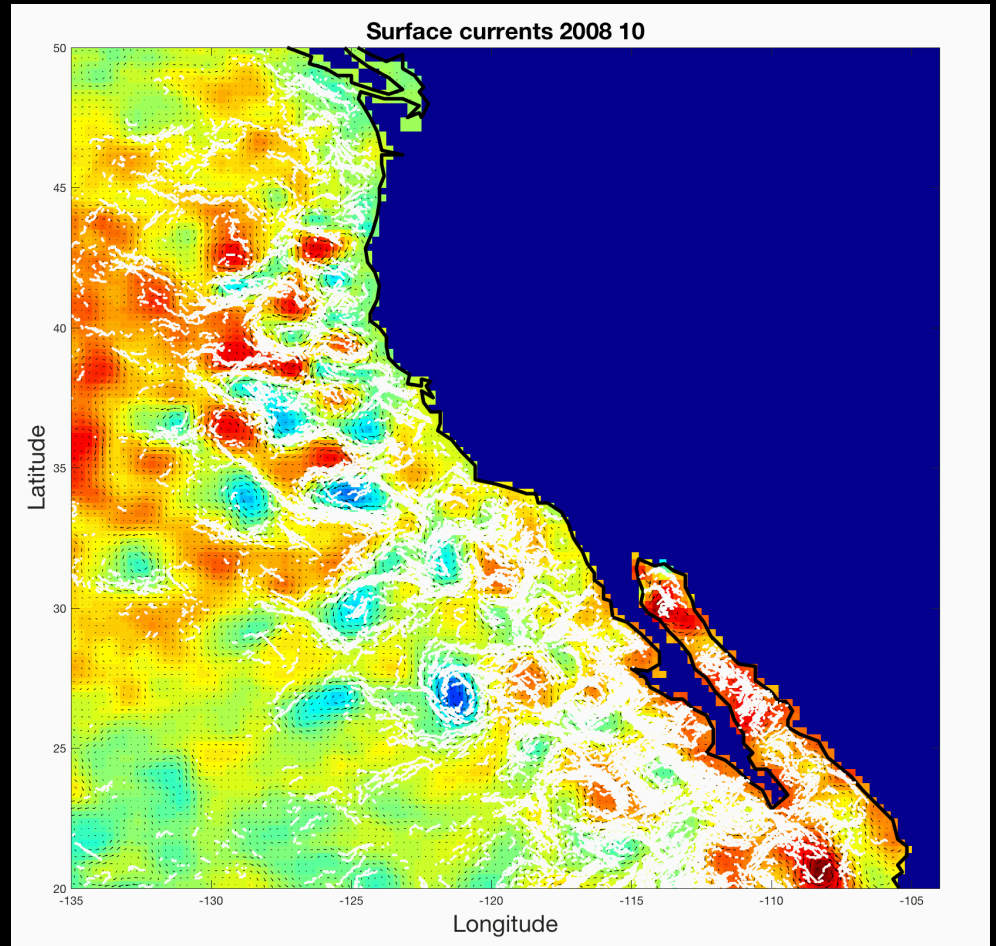
From Capet et al., 2008.

Frontogenesis theory

High strain regions are found at the periphery of mesoscale eddies, where SST fronts are also observed.

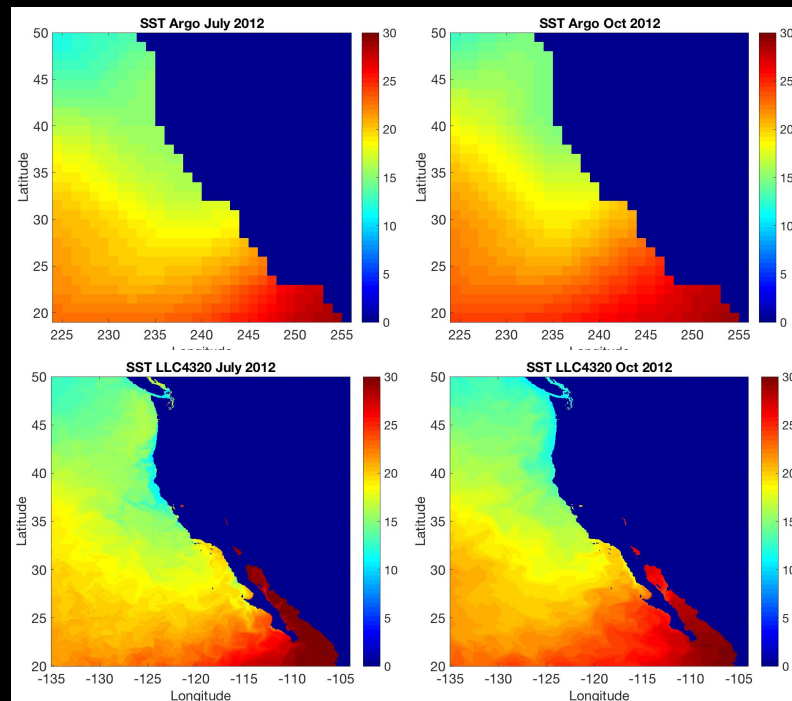


NASA



High resolution simulation

We use the MIT General Circulation Model (MITgcm) at a resolution of $1/48^\circ$ to analyze the SST fronts in the CCS. First, we look at the in-situ fields measured by Argo vs the simulated fields:

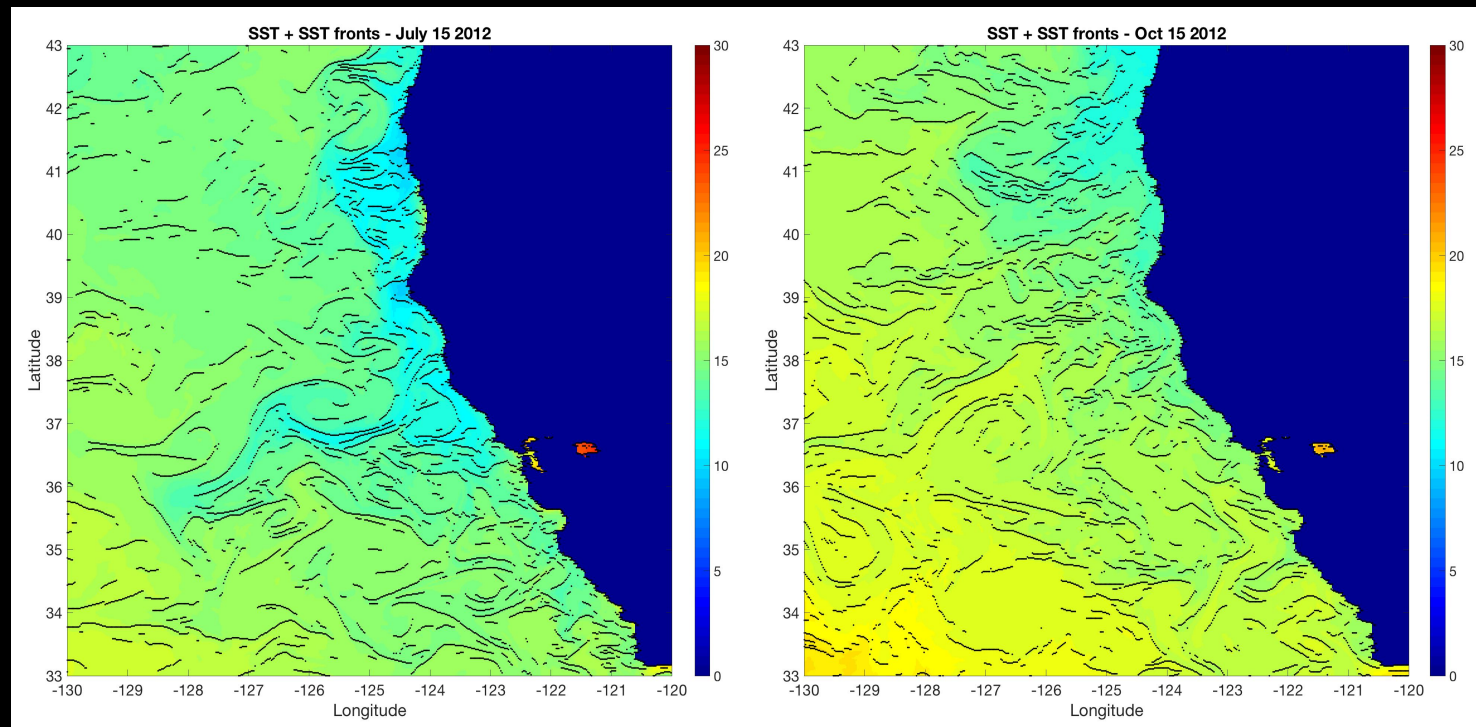


SST fronts detection in the model

$|\nabla(SST)|$ was computed over the whole CCS. The algorithm then searched for the peaks of local maximum: when the peaks had a relative height of at least $0.5^{\circ}\text{C}/\text{km}$, their location was saved for further analysis.

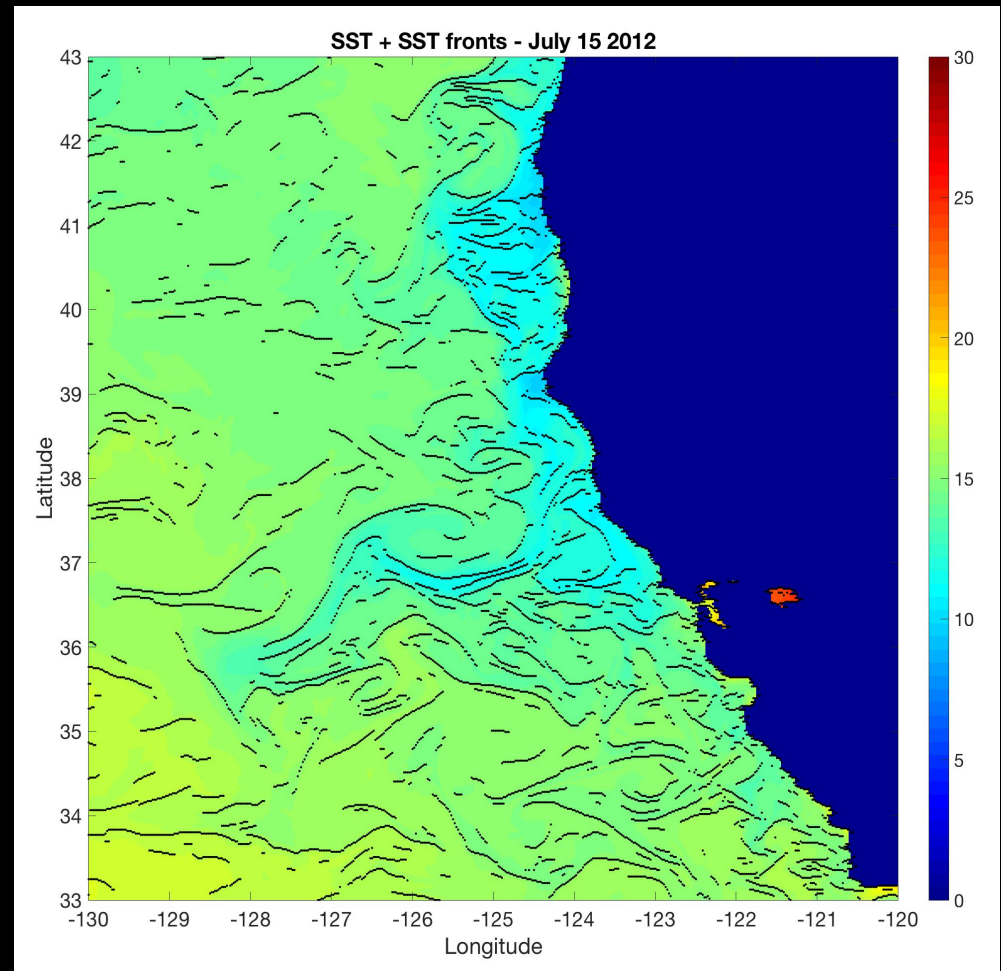
SST fronts – LLC4320

In the central CCS, we look at the SST and the SST fronts around the peak of the upwelling season, and in Fall when the season is almost over.



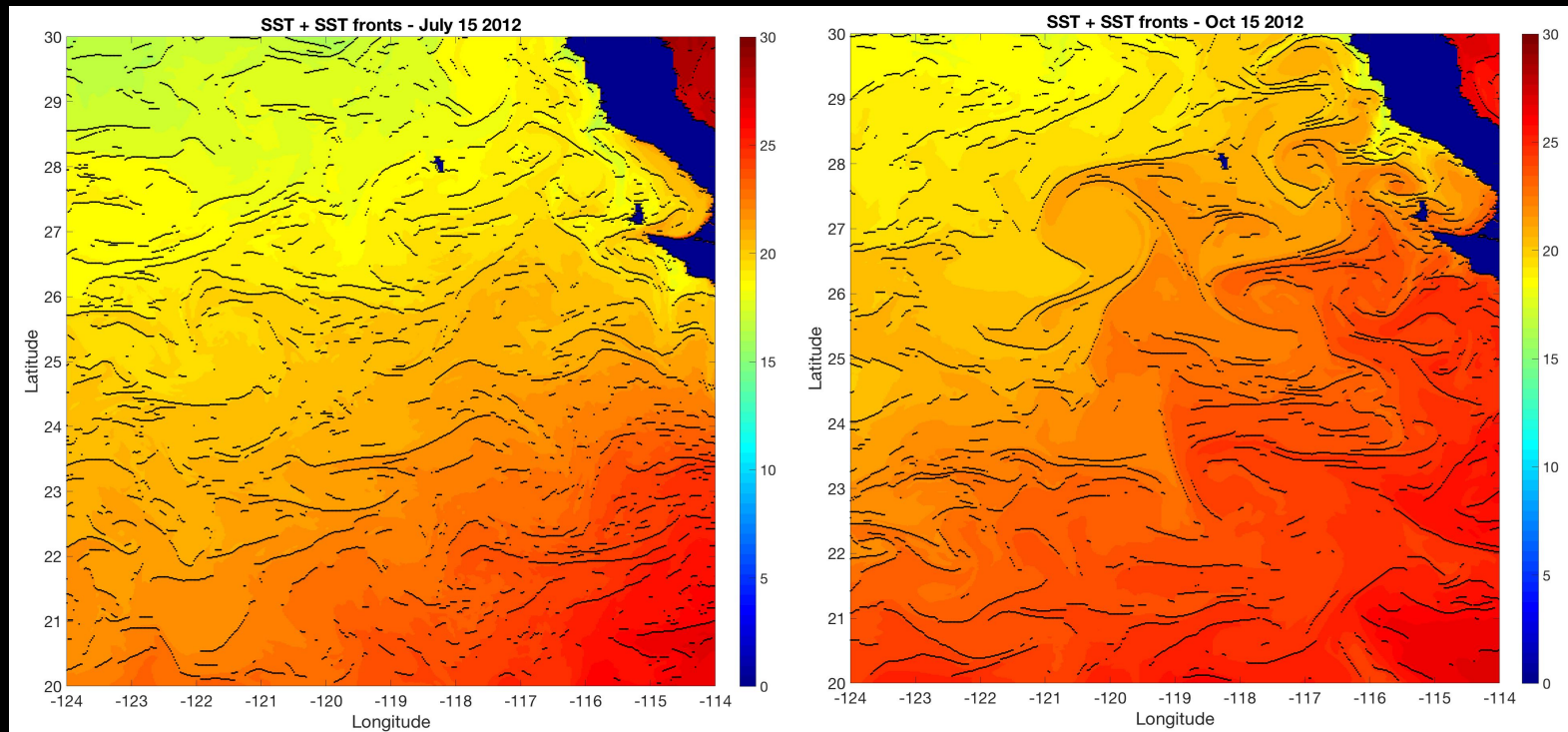
SST fronts – LLC4320

The cooler SST indicates upwelled, colder waters at the coast ($\sim 12^{\circ}\text{C}$). Small fronts are seen in the cold region, as well as longer « stretched » fronts offshore (cold filaments).



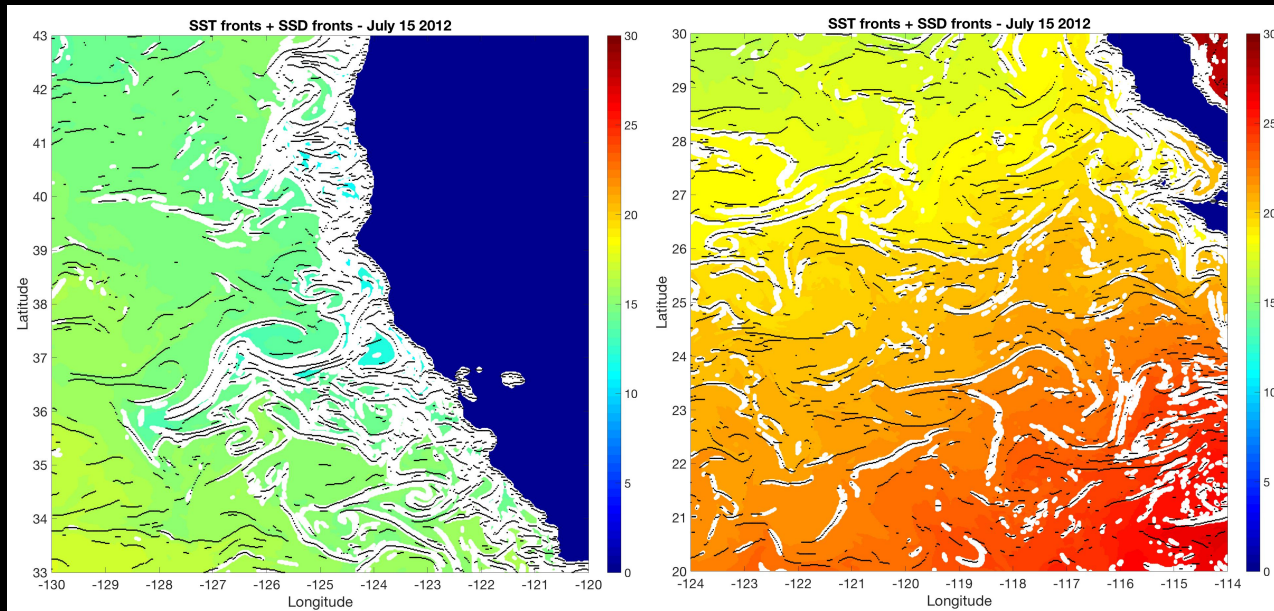
SST fronts – LLC4320

In the southern CCS, despite little to no sign of coastal upwelling, fronts are present, mostly similar to SST filaments found in the central CCS in aspect.



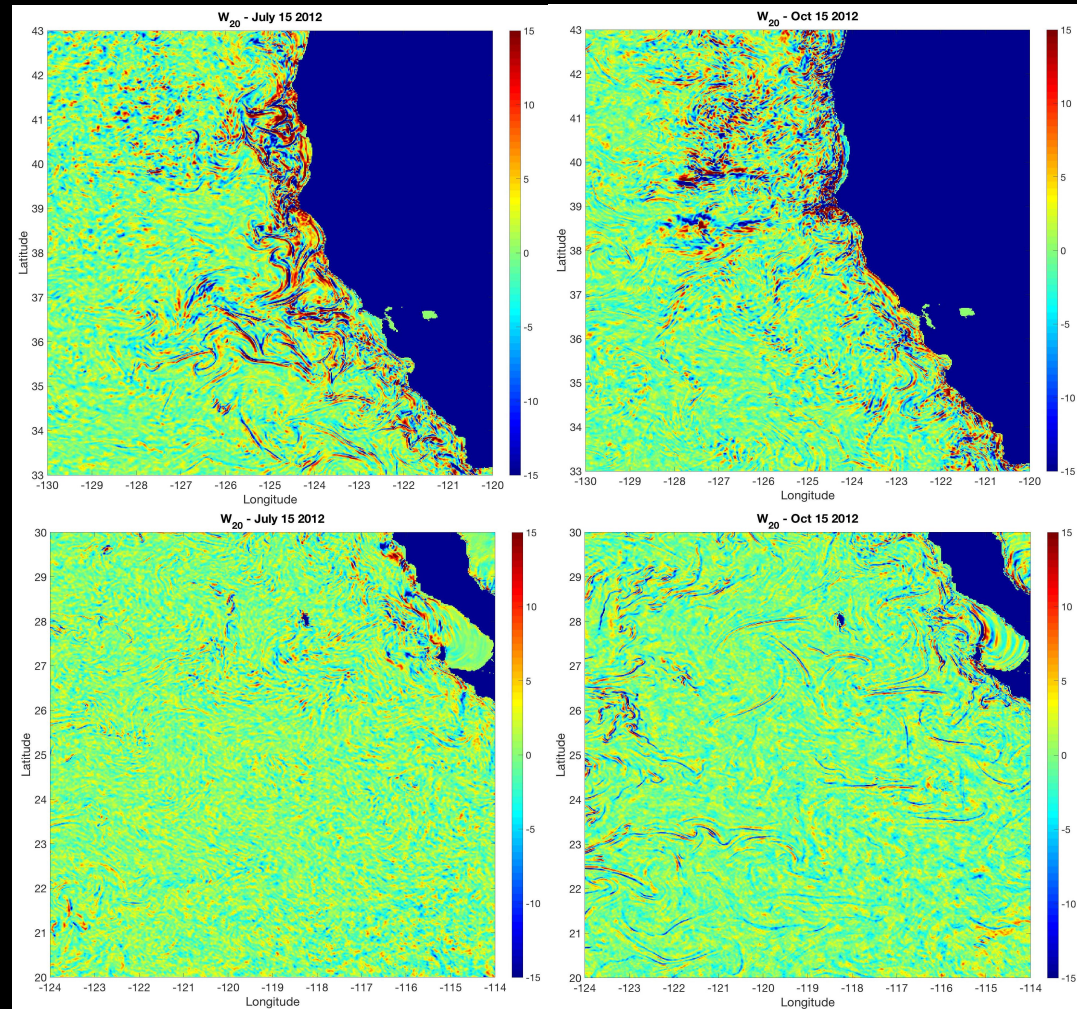
Density gradients – LLC4320

When deep waters are upwelled, a contrast of density appears at the ocean's surface, and density fronts are formed. In the ocean, density is a function of temperature, salinity and pressure; and density fronts are often associated with SST fronts.



Vertical velocities – LLC4320

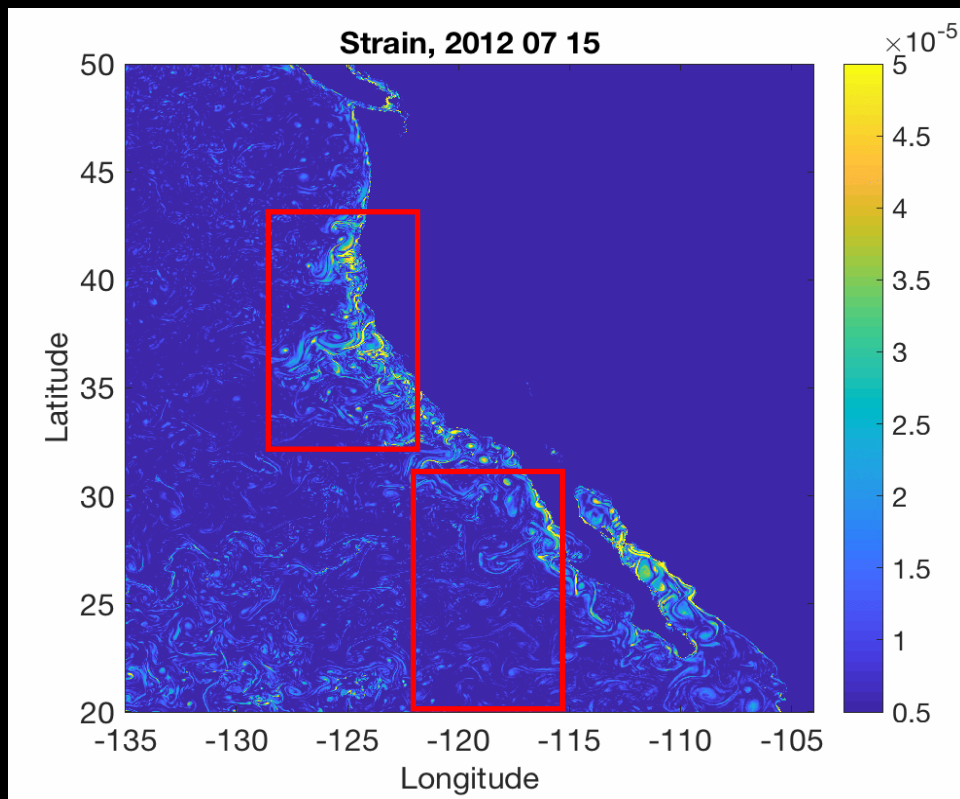
SST upwelling fronts are characterized by large vertical velocities (~ 10 - 20 m/day). W was taken at 20m depth in the whole CCS for the months of July and October, which reveals distinct patterns in the central and southern CCS.



Strain - LLC 4320

We derived the strain field from the horizontal velocities U and V:

$$\gamma = \sqrt{\left(\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}\right)^2 + \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}\right)^2}.$$



LLC 4320 findings

Central CCS

SST fronts

Coinciding density fronts

Strong vertical velocities

Large lateral strain

Southern CCS

SST fronts

Fewer density fronts

Weak vertical velocities

Small lateral strain

Then, what is causing the SST fronts to appear in the southern CCS?

Water masses

There are three major water masses present at the surface in the CCS: 1) the Subarctic Waters, 2) the Subtropical Waters, and 3) the Tropical Waters.

These waters with distinct properties and origins converge in southern CCS, to meet near Baja California in Summer and Fall.

We suggest that the water masses convergence off Baja California may impact the fronts in the region.

Water masses

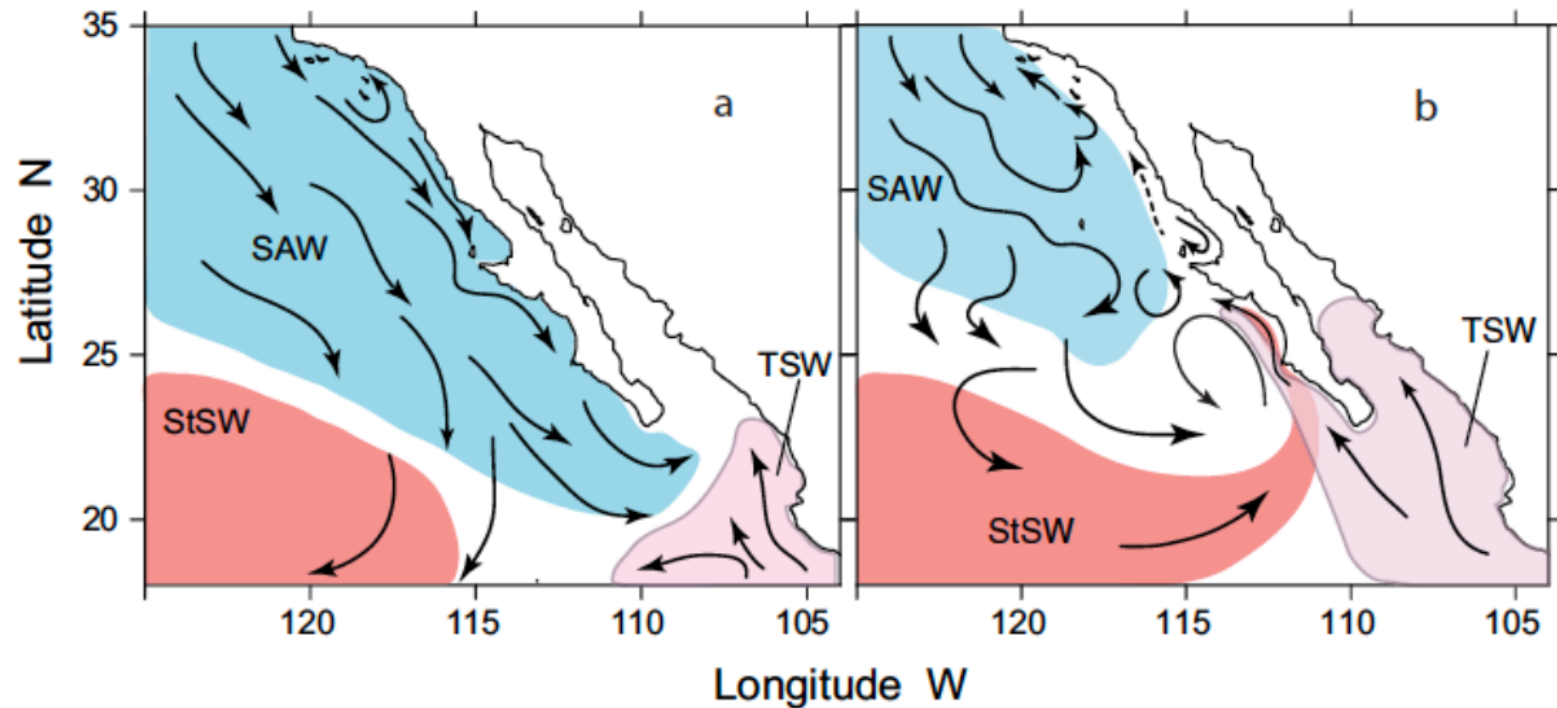


Figure 15. Schematic diagram of near-surface circulation and water mass interactions. (a) Winter-spring and (b) summer-fall. Approximate current direction is indicated by arrows. The dashed line indicates the likely existence of poleward flows. SAW, Subarctic Water; StSW, Subtropical Surface Water; TSW, Tropical Surface Water.

From Durazo, 2015.

Thermohaline compensation

Why are there fewer density fronts in the southern CCS?

→ At the ocean's surface, density is a function of temperature and salinity. However, both variables have opposite effects on density:

- When T increases, ρ decreases (lighter seawater)
- When S increases, ρ increases (heavier seawater)

→ Temperature (**thermo-**) and salinity (**haline**) can compensate each other, and cancel density variations out at the ocean's surface.

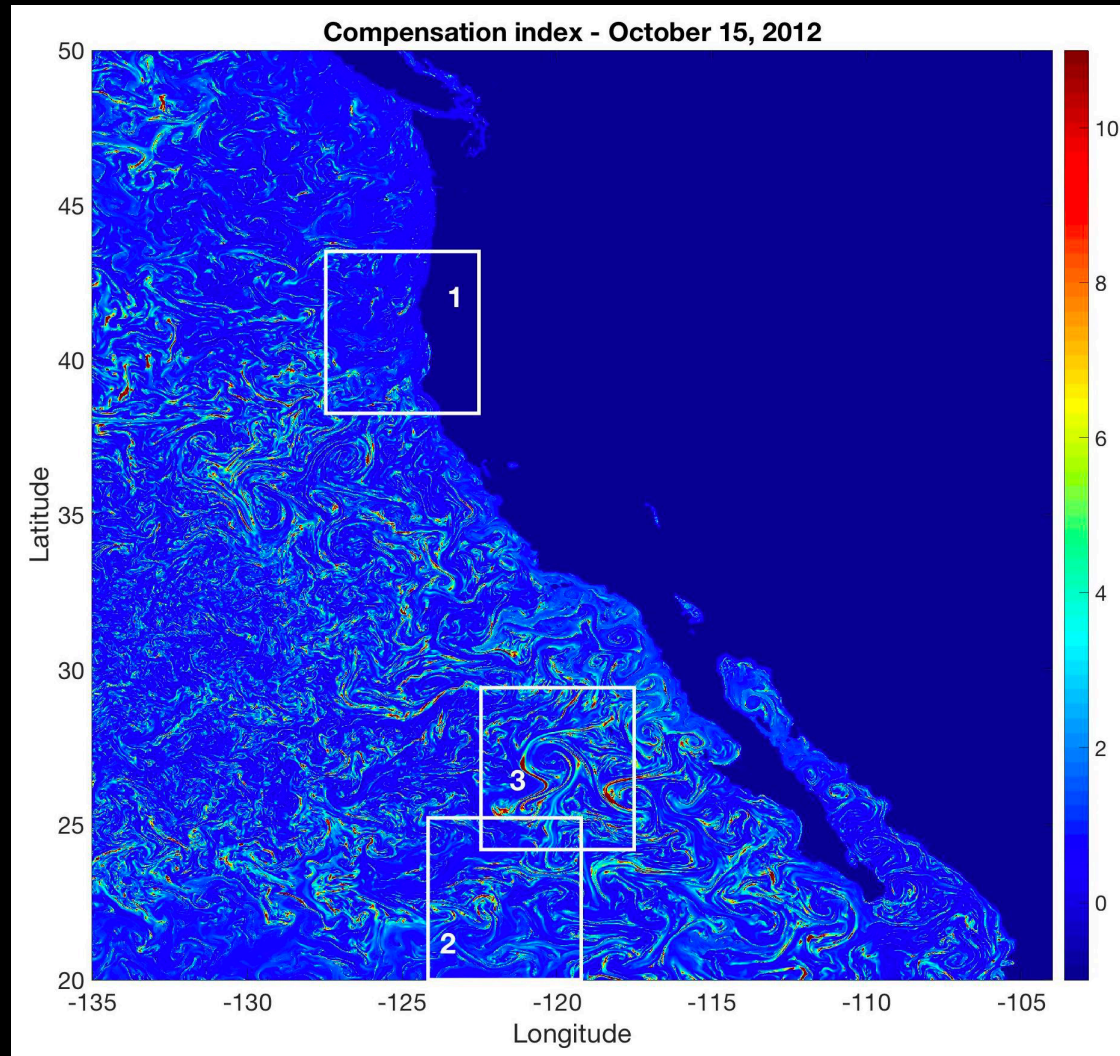
Thermohaline compensation

To quantify thermohaline compensation, we define the compensation index:

$$C_i = 10^3 \cdot \alpha \frac{|\nabla(SST)|}{|\nabla\rho|}$$

- $C_i \gg 1$: strong compensation and no density fronts,
- $C_i \sim 1$: no compensation, both SST fronts and density fronts are aligned.

Thermohaline compensation



Thermohaline compensation

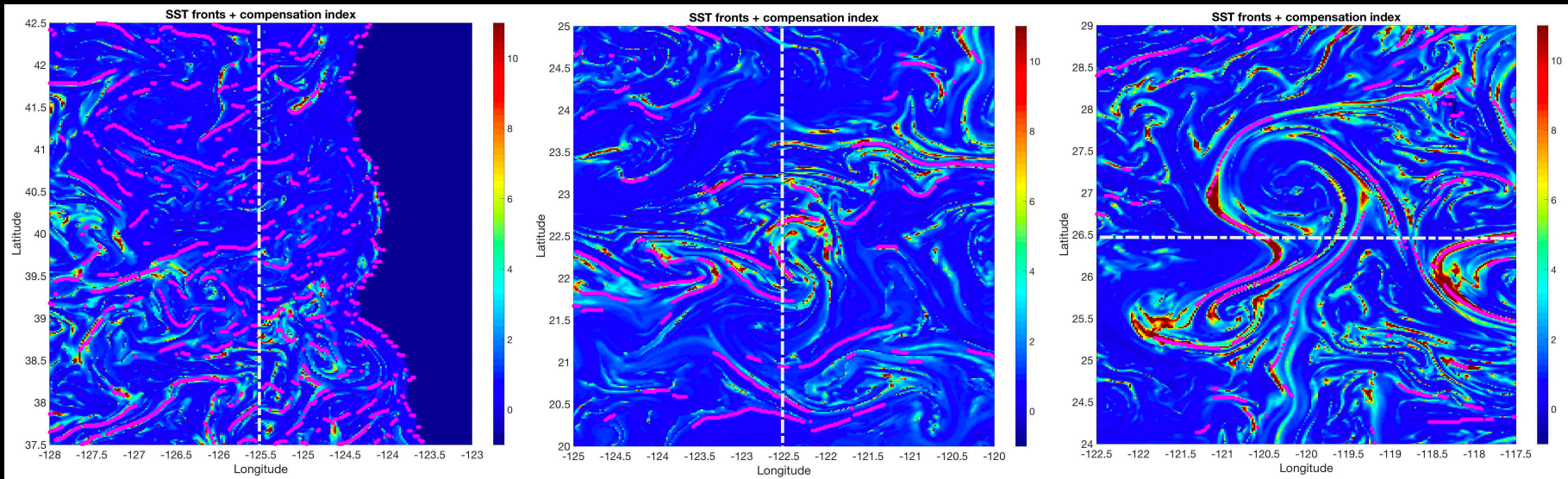
No compensation



Partial compensation



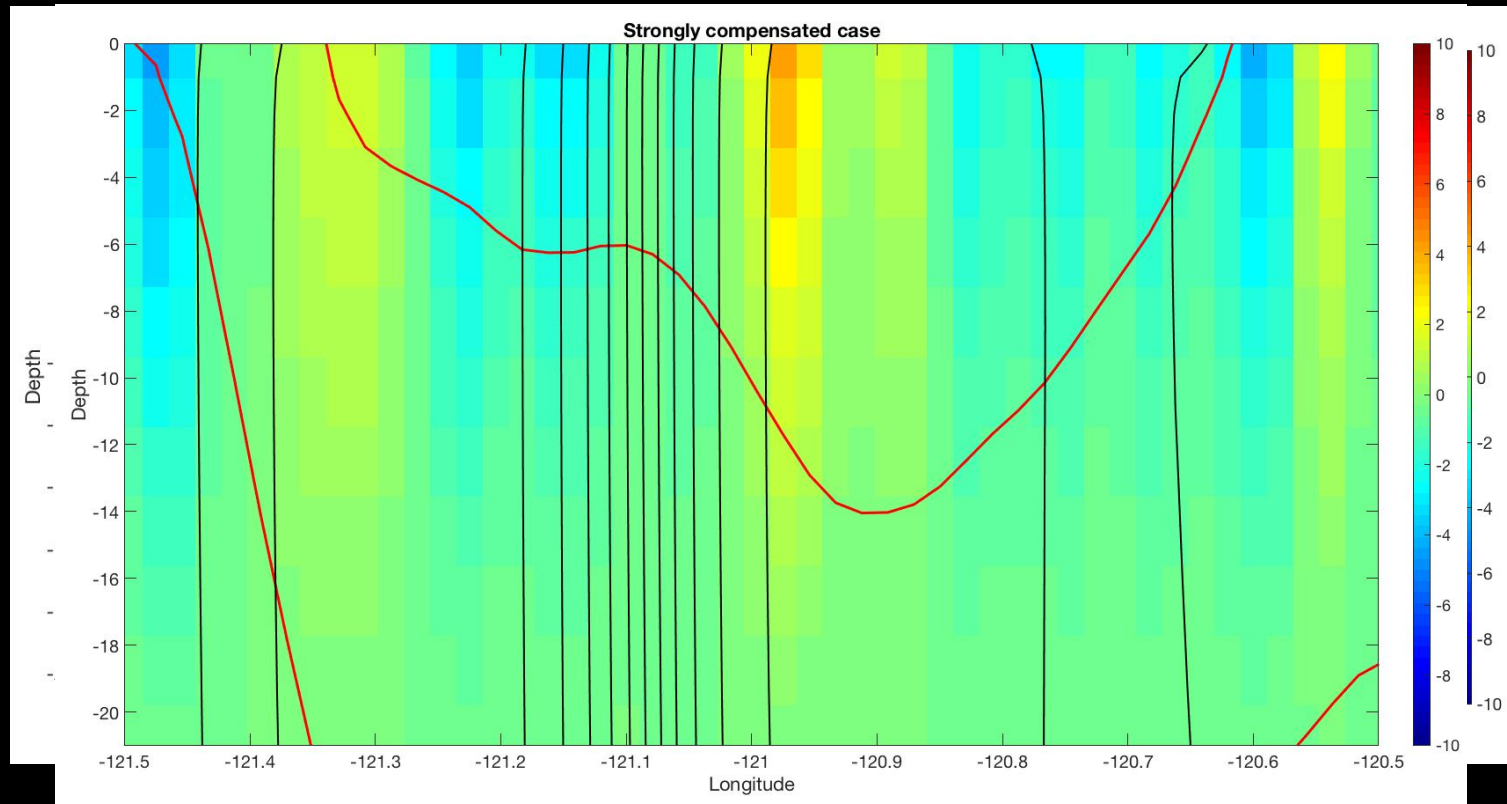
Full compensation



Compensation is not a binary process, rather it ranges on a spectrum from full compensation to no compensation at all, depending on C_i values:

Thermohaline compensation

Looking at vertical sections of fronts for each case, we see that the contours of **density** and temperature vary:



Summary

SST fronts in the southern CCS are associated to processes distinct from coastal upwelling, observed in the northern and central CCS.

Through high resolution simulations, frontal dynamics were explored in a region where limited in-situ observations have been reported: some SST fronts found off Baja California are found to be compensated, and behave as passive fronts, being advected by the background flow.

Thank you!

